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Lime Saturation in Portland Cements.

By Dr. HANS KÜHL.

THE report made by Dr. F. M. Lea[1] to the Kaiser Wilhelm Institute for Silicate Research at Berlin a short time ago on the work carried out by him and T. W Parker[2] on the quaternary system lime-silica-alumina-ferric oxide has aroused interest in Germany and has been of much use, especially with reference to the highest possible lime content of Portland cement. Practical experience has previously been the guide on this point, as is suggested in the formula which the writer deduced empirically from the condition of "frozen equilibrium" for the "lime standard" in special cases, such as white cement and Ferrari cement[3]. This formula gave a definite working basis for manufacture. An important advance was made when Lea and Parker produced a formula for the amount of lime in the whole region of the aluminate cements ($Al_2O_3 \geq 0.64Fe_2O_3$) which refers to the process of sintering, and which approximates very closely to the writer's formula for the lime standard.

In 1929 A. Guttmann and F. Gille[4] showed that the latest research on the constitution of Portland cement enabled the calculation of the maximum amount of lime in the hydraulic modulus which could be combined. Their work resulted in the introduction of the idea of a "lime modulus," that is, the ratio of the lime (excluding that combined with alumina), iron oxide (or manganese oxide), and sulphur trioxide to the silica. This ratio reaches a maximum of three when there is enough lime present to convert the silica completely to tricalcium silicate.

Guttmann and Gille's calculations ignored the magnesia and alkalis. This does not really matter in the case of magnesia since, according to the latest work of Büssem[5] and H. zur Strassen[5], either it occurs in Portland cement clinker free (as has been always assumed) or is absorbed in the space lattice of tetracalcium aluminoferrite. In either case it affects neither the lime nor the hydraulic modulus. It is otherwise with the alkalis. Though we do not know in what

compounds the alkalis are present, yet there is no doubt that they are actually combined and therefore take from the lime some of its acid constituents. This fact should be taken into account in calculations. As a preliminary the best method of doing this[6] is to assume that the alkalis and the sulphur trioxide in clinker almost neutralise each other, an assumption which is never quite accurate but may be taken as a "solution with the smallest error." Hence in the formula the alkalis and SO_3 in addition to the magnesia should be neglected. From the lime modulus of Guttmann and Gille it was only a small step to the " lime saturation factor " intrdoduced by the writer in 1930[7]. This step was small since it entailed the same considerations put forward by Guttmann and Gille for the lime modulus. It was, however, significant that it was accepted and gave a working basis to cement workers.

The " lime saturation factor " was defined as the ratio of the " actual " lime in a cement to the highest theoretical lime content, and the same idea was put forward independently a few months later by S. Rordam[8], who defined the " lime saturation ratio " as the ratio of the " actual lime " to the " maximum lime." These formulæ differ mainly in that the writer neglected the tetracalcium aluminoferrite, which had a doubtful significance in the clinker equilibrium conditions, while Rordam included this compound in his calculations. Events have proved Rordam to be right, and there is now no doubt that the compounds $3CaO.SiO_2$, $4CaO.Al_2O_3.Fe_2O_3$, and $3CaO.Al_2O_3$ (for cements rich in alumina) or $2CaO.Fe_2O_3$ (for cements rich in iron) should be used in the calculation of the lime saturation factor. If complete lime saturation is put equal to 100 and the lime saturation attained in any cement expressed as a percentage of complete saturation, the following formulæ for the lime saturation factor (L.S.F.) are obtained :

CASE I.—$Al_2O_3 \geq 0.64\ Fe_2O_3$

$$\text{L.S.F.} = 100 \times \frac{\text{effective lime}}{\text{maximum lime}} = \frac{100 \times CaO}{2.8SiO_2 + 1.65Al_2O_3 + 0.35Fe_2O_3}$$

CASE II.—$Al_2O_3 \leq 0.64\ Fe_2O_3$

$$\text{L.S.F.} = 100 \times \frac{\text{effective lime}}{\text{maximum lime}} = \frac{100 \times CaO}{2.8SiO_2 + 1.1Al_2O_3 + 0.7Fe_2O_3}$$

In these formulæ the manganese oxide has been neglected for the sake of simplicity. A. Guttmann and F. Gille[9] have shown that manganese oxide can be added to the ferric oxide for the purposes of calculation in cements which contain this compound.

The whole of the chemistry of Portland cement clinker would be condensed by this into a simple convenient formula if the cement manufacturing process were perfect and if 100 per cent. lime saturation could be attained. Cement with a lime saturation of 100 could be produced from a raw mix only under ideal conditions, that is, if a correctly proportioned raw mix could be burned and cooled in such a manner that chemical equilibrium was attained at all times during the process. In practice this cannot be done ; the difficulties lie not in the burning, as might be supposed, but in the cooling. As has been shown by E. Spohn[10] and S. Solacolu[11] for the field they investigated, and by F. M. Lea[12]

for the whole field of Portland cement up to Ferrari cement[13], chemical equilibrium is attained during sintering, but during the subsequent cooling the reactions which should occur are held back. On these grounds Spohn has described Portland cement clinker as a " frozen equilibrium," and this description is confirmed by the investigations of Lea and Parker.

The freezing of the equilibrium attained at the high temperature of sintering results in less lime of the hydraulic modulus being combined than would be expected from the lime saturation formula. This rule holds for all systems which contain more alumina than iron oxide (in equivalents) and hence for all cements between white cement and Ferrari cement. Actually there is an important difference between the " frozen equilibria " for true Portland cements and for cements of the Ferrari type.

Considering first a normal Portland cement raw mix, there is formed besides a comparatively low-lime melt a system of solid compounds which is much richer in lime than the melt. A mass with a lime saturation factor of 100 during sintering must therefore always contain free lime in the solid phase besides the compounds rich in lime which has not been taken up in the melt. If this is cooled slowly under equilibrium conditions the free lime reacts with the low-lime melt to form compounds rich in lime and thus disappears. In practice, this does not occur during cooling, so that the lime which was not combined during sintering finally appears in the cooled clinker and it is immaterial whether the melt sets to a glass or crystallises out. Hence besides the lime-saturated compounds dicalcium silicate and pentacalcium trialuminate are present.

It is different in the case of high-iron cements, as has been emphasised by F. M. Lea, where the ratio of alumina to iron oxide is equal to one. For cements of this type with a lime saturation factor of 100 besides a lime-rich melt a comparatively low-lime system of solid phases form from the raw mix in which dicalcium silicate appears as well as tricalcium silicate. This lowering of lime in the solid phases means that the melt contains more lime than the complete saturation of its acid constituents requires. If this is cooled slowly the excess lime in the melt combines with dicalcium silicate to form tricalcium silicate. In practice this change does not occur, and a clinker is obtained which contains free lime whether the residual melt crystallises out or sets to a glass, the free lime being in solution in the melt.

It is apparent that there must be between normal Portland cements and Ferrari cement a field in which the solid phases and the melts have the same or nearly the same lime content, and in which complete or almost complete lime saturation is attainable. Cements of this type are not very different in composition from Ferrari cement and are somewhat richer in alumina.

Besides the composition of the melt its amount is also important in the structure of the cooled clinker. Lea's investigations show that the differences in the composition of cement raw materials do not have a great influence on the ratio of the amounts of the solid phases to the melts for normal Portland cements. But for cements with an alumina ratio $\frac{Al_2O_3}{Fe_2O_3}$ equal to about 1.38 large amounts

of melt are formed at low temperatures (the more so the higher is the absolute amount of alumina and iron oxide) so that this type of cement is very easy to burn.

The writer found in 1923[14] that cements of exceptionally high early strength (Bauxitland cement, Kühl cement) were obtained if the silica and alumina ratios were reduced to about 1.2. The work of Lea has given the key to the understanding of this, and shows that for cements of this type the possibility of attaining an almost complete lime saturation depends on the formation of large quantities of melt at a comparatively low temperature.

The writer's co-workers, Spohn and Solacolu, have shown that the well-known formula of Bogue for calculating the potential analysis of cement has a very limited application in the commercial production of cements because they usually do not attain equilibrium. Therefore the formula for lime saturation has only a theoretical interest and gives no information which will enable manufacturers to fix the best lime content of the raw mix. On account of this there has been an attempt to produce a formula which will give the actual lime for works' use.

In looking for such a formula it must be kept in mind that the compositions used in practice in the cement industry are too diverse to be covered by a single rule. L. Forsén[15] has dealt with this by limiting the lime in combination between an upper and a lower figure. He gave a formula for the maximum lime containing a variable factor f to allow for this range :

$$CaO_{max} = 2.8SiO_2 + 1.4Fe_2O_3 + f(Al_2O_3 - 0.64Fe_2O_3)$$

in which f can vary between 1.0 and 1.65. The correct value for any particular condition depends on the type of raw materials, the amount of flux, the rate of burning and cooling, and other factors.

If the limiting values of 1.65 and 1.0 are used in Forsén's formula the upper and lower limits for the maximum lime combination are given by the following expressions :

I.—($f = 1.65$) : $CaO_{max} = 2.8SiO_2 + 1.65Al_2O_3 + 0.35Fe_2O_3$ (Forsén).
II.—($f = 1.0$) : $CaO_{max} = 2.8SiO_2 + 1.0Al_2O_3 + 0.76Fe_2O_3$.

Formula I coincides with the formula for complete lime saturation, i.e. for a lime saturation factor of 100. Forsén has shown that although certain cement works can, on account of special circumstances, attain complete lime saturation, for the great majority of works formula II is of greater interest because it shows the amount of lime that can be used in practice by all cement works without free lime being present in the cooled clinker.

In establishing a formula for the lime standard [16] the writer has been concerned chiefly with the most probable conditions likely to be obtained. It has been assumed (a deduction from the work of Spohn and Solacolu and the theoretical investigations of L. A. Dahl[17]) that the technical limit of lime combination must be near that given by the theory that clinker is in a condition of frozen equilibrium. The lime combination which was attained in the best Portland cements was then found by an examination of their compositions. Finally, the average value of the various figures was taken as the "lime standard," i.e. the most

probable amount of lime which could be used by a cement works. The following formula gives its value :

$$CaO_{stan.} = 2.8SiO_2 + 1.1Al_2O_3 + 0.7Fe_2O_3 \quad .. \quad \text{(Kühl)}$$

This is an empirical formula and gives no information about the individual compounds actually formed. It is only a numerical figure and does not imply that the sintered clinker actually consists of tricalcium silicate, dicalcium aluminate, and dicalcium ferrite.

The standard formula coincides with the saturation formula for the field of of the ferrite cements ($Al_2O_3 < 0.64Fe_2O_3$), for on account of the relation between tetracalcium aluminoferrite and dicalcium ferrite (as in the case of Ferrari cement)

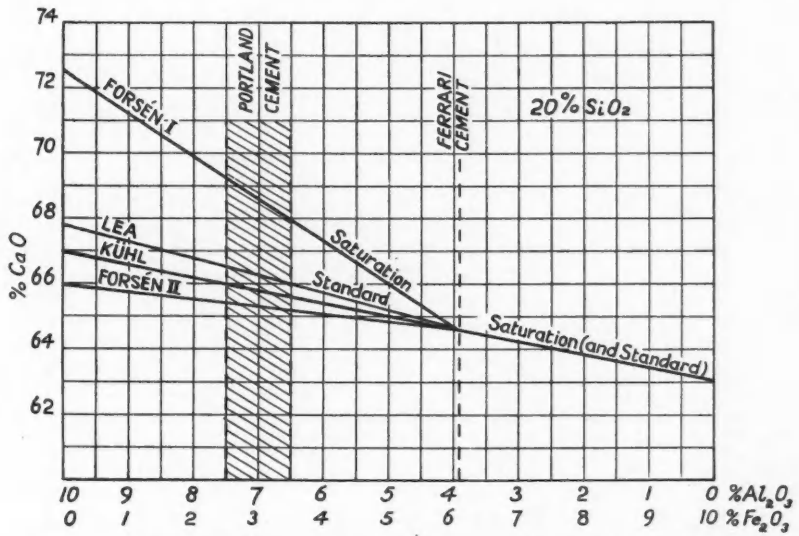

Fig. 1.—Effect of alumina modulus on lime saturation and lime standard of Portland cement according to Lea, Forsén and Kühl.

practically complete lime saturation can be attained. In the field of the aluminate cements ($Al_2O_3 > 0.64Fe_2O_3$) it lies near the lower limit of the field given by Forsén, and represents within the field that line on which and in the neighbourhood of which the points accumulate if a diagram is made of the actual attainable lime for all cement works.

In a similar manner Lea[18] has produced a formula for maximum lime combination which is based on the results of research carried out by him and Parker in the whole field of the aluminate cements between white cement (without iron oxide) and Ferrari cement ($Al_2O_3 = 0.64Fe_2O_3$) :

$$CaO_{max} = 2.8SiO_2 + 1.18Al_2O_3 + 0.65Fe_2O_3 \quad .. \quad .. \quad .. \quad \text{(Lea)}$$

It can be seen (as Lea has already hinted) that this formula is very little different from the writer's.

In order to give an idea how small is this difference between Lea's purely scientific formula and the writer's formula developed from practical experience, and to show how these two fit in with Forsén's, the relations are shown in Fig. 1. In this series cements have been used containing about 20 per cent. silica, 10 per cent. sesquioxides, and with an alumina modulus between infinity and 0.

It can be seen how the limiting lines of Forsén include a field which from Ferrari cement to white cement widens, and in the field of true Portland cements there is a considerable distance between the limits for maximum lime. Within these limits the lines of Lea and the writer give the field containing compositions which occur most frequently. Since there is only a very small difference which can scarcely be counted in practice between these two lines, it can be concluded that for most Portland cements the actual attainable lime is the same as for that in which equilibrium is attained during sintering, i.e. the equilibrium produced according to the investigations of Lea and Parker in the quaternary system lime-silica-alumina-iron oxide.

This is a very important deduction, and it is suggested that the conception of the " lime standard " for that amount of lime of the hydraulic modulus which can be combined at sintering temperature according to the rules of chemical equilibrium be adopted and that the writer's empirical formula be replaced by the more scientific one of Lea and Parker,

$$CaO_{stan.} = 2.8SiO_2 + 1.18Al_2O_3 + 0.65Fe_2O_3.$$

From this formula the lime standard of any given cement can be obtained if the actual combined lime is expressed as a percentage of the amount obtained from the lime standard :

$$\text{Lime standard} = \frac{100 \times CaO}{2.8SiO_2 + 1.18Al_2O_3 + 0.65Fe_2O_3}$$

For technical purposes these considerations show that for a particular cement works the amount of the probable attainable lime (as standard lime) is that lime in the hydraulic modulus which can be combined at sintering temperature according to the equilibrium conditions in the quaternary diagram as worked out by Lea and Parker. When there are considerable deviations, as found by Forsén for two Swedish cement works, they are due to exceptional conditions and cannot at present be included in a general theory.

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Volumes and Weights of Gases from Rotary Kilns.

THE following tables give the volumes and weights of rotary-kiln exit-gases when various percentages of excess air are present. For the data on which the following tables are based see CEMENT AND CEMENT MANUFACTURE, 1935, p. 190. Reference has also been made to an article by Howe, CEMENT AND CEMENT MANUFACTURE, 1933, p. 237.

EXCESS AIR AS PERCENTAGE OF COMBUSTION AIR.

Per cent. standard coal.	Percentage oxygen in rotary-kiln exit-gases.					
	0·5	1·0	1·5	2·0	2·5	3·0
20·0	2·78	5·70	8·77	12·00	15·42	19·04
20·5	2·77	5·68	8·74	11·96	15·37	18·98
21·0	2·76	5·66	8·72	11·92	15·32	18·92
21·5	2·75	5·64	8·69	11·88	15·27	18·86
22·0	2·74	5·62	8·67	11·84	15·22	18·80
22·5	2·73	5·61	8·64	11·81	15·18	18·74
23·0	2·72	5·59	8·62	11·78	15·14	18·68
23·5	2·72	5·57	8·59	11·75	15·10	18·62
24·0	2·71	5·56	8·57	11·72	15·06	18·57
24·5	2·71	5·55	8·54	11·69	15·02	18·52
25·0	2·70	5·54	8·52	11·66	14·98	18·47
25·5	2·70	5·52	8·50	11·63	14·94	18·42
26·0	2·69	5·50	8·49	11·60	14·90	18·38
26·5	2·68	5·49	8·47	11·57	14·86	18·34
27·0	2·67	5·48	8·45	11·54	14·83	18·30
27·5	2·67	5·47	8·43	11·51	14·80	18·26
28·0	2·66	5·46	8·42	11·49	14·77	18·22
28·5	2·66	5·45	8·40	11·47	14·74	18·19
29·0	2·65	5·44	8·38	11·45	14·71	18·16
29·5	2·65	5·43	8·37	11·43	14·68	18·13
30·0	2·64	5·42	8·35	11·41	14·65	18·10

Weights of Excess Air in Kiln Gases in lb. per Clinker Ton.

Per cent. standard coal.	Percentage oxygen in exit-gases.					
	0·5	1·0	1·5	2·0	2·5	3·0
20·0	122	251	386	528	678	837
20·5	125	256	394	539	693	855
21·0	127	261	402	550	707	873
21·5	130	267	411	562	722	891
22·0	133	272	419	573	736	909
22·5	135	278	427	584	751	927
23·0	138	283	436	596	765	945
23·5	140	288	444	607	780	963
24·0	143	294	452	618	794	980
24·5	146	299	460	629	809	997
25·0	148	305	468	641	823	1,015
25·5	151	310	476	652	837	1,033
26·0	153	315	485	663	852	1,050
26·5	156	320	493	674	866	1,068
27·0	159	326	501	685	880	1,086
27·5	161	331	509	696	895	1,104
28·0	164	336	518	707	909	1,122
28·5	166	341	526	718	923	1,140
29·0	169	347	534	730	938	1,158
29·5	172	352	543	741	952	1,176
30·0	174	357	551	753	966	1,194

Vol. of Excess Air in Kiln Gases in Cubic Feet per Clinker Ton.

(GAS TEMPERATURE 450 DEG. F.)

Per cent. standard coal.	Percentage oxygen in exit-gases.					
	0·5	1·0	1·5	2·0	2·5	3·0
20·0	2,808	5,755	8,869	12,137	15,600	19,265
20·5	2,868	5,882	9,061	12,399	15,938	19,676
21·0	2,928	6,007	9,253	12,662	16,275	20,087
21·5	2,987	6,133	9,445	12,924	16,613	20,498
22·0	3,047	6,258	9,636	13,187	16,950	20,909
22·5	3,107	6,384	9,828	13,449	17,288	21,320
23·0	3,167	6,510	10,020	13,708	17,616	21,725
23·5	3,227	6,634	10,211	13,966	17,944	22,130
24·0	3,287	6,760	10,401	14,225	18,272	22,534
24·5	3,346	6,886	10,592	14,483	18,600	22,939
25·0	3,407	7,010	10,782	14,742	18,928	23,344
25·5	3,466	7,130	10,969	14,995	19,261	23,755
26·0	3,527	7,250	11,156	15,247	19,594	24,167
26·5	3,586	7,370	11,342	15,500	19,928	24,578
27·0	3,646	7,489	11,529	15,752	20,261	24,990
27·5	3,706	7,610	11,716	16,005	20,594	25,401
28·0	3,766	7,732	11,905	16,268	20,920	25,815
28·5	3,826	7,855	12,096	16,530	21,246	26,229
29·0	3,885	7,978	12,287	16,793	21,573	26,644
29·5	3,946	8,101	12,478	17,055	21,899	27,058
30·0	4,006	8,226	12,669	17,318	22,225	27,472

Total Weight of Kiln Exit-gases in lb. per ton of Clinker at Various Percentages of Standard Coal and Oxygen.

Per cent. standard coal.	Percentage oxygen in exit-gases.						
	0·0	0·5	1·0	1·5	2·0	2·5	3·0
20·0	8,822	8,944	9,072	9,208	9,350	9,500	9,659
20·5	8,943	9,068	9,199	9,337	9,482	9,636	9,798
21·0	9,066	9,193	9,327	9,468	9,616	9,773	9,939
21·5	9,196	9,226	9,463	9,607	9,758	9,918	10,087
22·0	9,319	9,452	9,591	9,738	9,892	10,055	10,228
22·5	9,440	9,575	9,718	9,867	10,024	10,191	10,367
23·0	9,564	9,702	9,847	10,000	10,160	10,329	10,509
23·5	9,685	9,825	9,973	10,129	10,292	10,465	10,647
24·0	9,805	9,948	10,099	10,257	10,423	10,599	10,785
24·5	9,927	10,073	10,226	10,387	10,556	10,736	10,924
25·0	10,050	10,198	10,355	10,518	10,691	10,873	11,065
25·5	10,173	10,324	10,483	10,649	10,825	11,010	11,206
26·0	10,294	10,447	10,609	10,779	10,957	11,146	11,344
26·5	10,416	10,572	10,736	10,909	11,090	11,282	11,484
27·0	10,538	10,697	10,864	11,039	11,223	11,418	11,654
27·5	10,659	10,820	10,990	11,168	11,355	11,554	11,763
28·0	10,782	10,946	11,118	11,300	11,489	11,691	11,904
28·5	10,904	11,070	11,245	11,430	11,622	11,827	12,044
29·0	11,025	11,194	11,372	11,559	11,755	11,963	12,183
29·5	11,148	11,320	11,500	11,691	11,889	12,100	12,324
30·0	11,269	11,443	11,626	11,820	12,022	12,235	12,463

Total Volume of Kiln Exit-gases in Cubic feet per ton of Clinker at Various Percentages of Standard Coal and Oxygen.

GAS TEMPERATURE 450 DEG. F.

Per cent. standard coal.	Percentage oxygen in exit-gases.						
	0·0	0·5	1·0	1·5	2·0	2·5	3·0
20·0	220,976	223,784	226,731	229,845	233,113	236,576	240,241
20·5	223,672	226,540	229,554	232,733	236,071	239,610	243,348
21·0	226,364	229,292	232,371	235,617	239,026	242,639	246,451
21·5	229,038	232,025	235,171	238,483	241,962	245,651	249,536
22·0	231,724	234,771	237,982	241,360	244,911	248,674	252,633
22·5	234,421	237,528	240,805	244,249	247,870	251,709	255,741
23·0	237,148	240,315	243,658	247,168	250,856	254,764	258,873
23·5	239,810	243,037	246,444	250,021	253,776	257,754	261,940
24·0	242,518	245,805	249,278	252,919	256,743	260,790	265,052
24·5	245,155	248,501	252,041	255,747	259,638	263,755	268,094
25·0	247,866	251,273	254,876	258,648	262,608	266,794	271,210
25·5	250,579	254,045	257,709	261,548	265,574	269,840	274,334
26·0	253,245	256,772	260,495	264,401	268,492	272,839	277,412
26·5	255,935	259,521	263,305	267,277	271,435	275,863	280,513
27·0	258,659	262,305	266,148	270,188	274,411	278,920	283,649
27·5	261,324	265,030	268,934	273,040	277,329	281,918	286,725
28·0	264,035	267,801	271,767	275,940	280,303	284,955	289,850
28·5	266,713	270,539	274,568	278,809	283,243	287,959	292,942
29·0	269,400	273,285	277,378	281,687	286,193	290,973	296,044
29·5	272,119	276,065	280,220	284,597	289,174	294,018	299,177
30·0	274,780	278,786	283,006	287,449	292,098	297,005	302,252

Density of Kiln Exit-gases.

The following tables have been calculated from the preceding tables of weights and volumes of kiln gases, the temperature correction being made according to Charles's Law.

DENSITY OF KILN EXIT-GASES IN LBS. PER CUBIC FOOT.

(1) GAS TEMPERATURE 450 DEG. F.

Per cent. standard coal.	Percentage oxygen in exit-gases.						
	0·0	0·5	1·0	1·5	2·0	2·5	3·0
20·0	0·03992	0·03997	0·04001	0·04006	0·04011	0·04016	0·04020
20·5	0·03999	0·04004	0·04008	0·04013	0·04018	0·04023	0·04027
21·0	0·04006	0·04011	0·04015	0·04020	0·04025	0·04030	0·04034
21·5	0·04013	0·04018	0·04022	0·04027	0·04032	0·04037	0·04041
22·0	0·04020	0·04025	0·04029	0·04034	0·04038	0·04043	0·04048
22·5	0·04027	0·04031	0·04036	0·04040	0·04044	0·04049	0·04054
23·0	0·04033	0·04037	0·04042	0·04046	0·04050	0·04055	0·04060
23·5	0·04039	0·04043	0·04048	0·04052	0·04056	0·04060	0·04065
24·0	0·04044	0·04049	0·04053	0·04057	0·04061	0·04065	0·04070
24·5	0·04049	0·04054	0·04058	0·04062	0·04066	0·04070	0·04075
25·0	0·04055	0·04059	0·04063	0·04067	0·04071	0·04075	0·04080
25·5	0·04060	0·04064	0·04068	0·04072	0·04076	0·04080	0·04085
26·0	0·04065	0·04069	0·04073	0·04077	0·04081	0·04085	0·04090
26·5	0·04070	0·04074	0·04078	0·04082	0·04086	0·04090	0·04094
27·0	0·04074	0·04079	0·04083	0·04086	0·04090	0·04095	0·04098
27·5	0·04079	0·04083	0·04087	0·04090	0·04094	0·04099	0·04102
28·0	0·04083	0·04088	0·04092	0·04095	0·04099	0·04104	0·04107
28·5	0·04088	0·04093	0·04096	0·04099	0·04103	0·04108	0·04111
29·0	0·04092	0·04097	0·04100	0·04104	0·04108	0·04112	0·04115
29·5	0·04097	0·04101	0·04104	0·04108	0·04112	0·04116	0·04119
30·0	0·04101	0·04105	0·04108	0·04112	0·04116	0·04120	0·04123

(2) GAS TEMPERATURE 475 DEG. F.

Per cent. standard coal.	Percentage oxygen in exit-gases.						
	0·0	0·5	1·0	1·5	2·0	2·5	3·0
20·0	0·03885	0·03890	0·03894	0·03899	0·03904	0·03908	0·03912
20·5	0·03892	0·03897	0·03901	0·03906	0·03911	0·03915	0·03919
21·0	0·03899	0·03904	0·03908	0·03913	0·03917	0·03921	0·03925
21·5	0·03906	0·03911	0·03915	0·03919	0·03924	0·03928	0·03932
22·0	0·03913	0·03917	0·03922	0·03926	0·03930	0·03934	0·03938
22·5	0·03919	0·03923	0·03928	0·03932	0·03936	0·03941	0·03945
23·0	0·03925	0·03929	0·03934	0·03938	0·03942	0·03946	0·03951
23·5	0·03931	0·03935	0·03939	0·03943	0·03947	0·03951	0·03956
24·0	0·03936	0·03940	0·03944	0·03948	0·03952	0·03956	0.03961
24·5	0·03941	0·03945	0·03949	0·03953	0·03957	0·03961	0·03966
25·0	0·03946	0·03950	0·03954	0·03958	0·03962	0·03966	0·03971
25·5	0·03951	0·03955	0·03959	0·03963	0·03967	0·03971	0·03976
26·0	0·03956	0·03960	0·03964	0·03967	0·03971	0·03975	0·03980
26·5	0·03961	0·03965	0·03969	0·03972	0·03976	0·03980	0·03984
27·0	0·03966	0·03970	0·03974	0·03977	0·03980	0·03984	0·03988
27·5	0·03970	0·03974	0·03978	0·03981	0·03984	0·03988	0·03992
28·0	0·03975	0·03979	0·03982	0·03985	0·03989	0·03993	0·03996
28·5	0·03979	0·03983	0·03986	0·03989	0·03993	0·03997	0·04000
29·0	0·03983	0·03987	0·03990	0·03994	0·03998	0·04001	0·04004
29·5	0·03987	0·03991	0·03994	0·03998	0·04002	0·04005	0·04008
30·0	0·03991	0·03995	0·03998	0·04002	0·04006	0·04009	0·04012

(3) GAS TEMPERATURE 500 DEG. F.

Per cent. standard coal.	Percentage oxygen in exit-gases.						
	0·0	0·5	1·0	1·5	2·0	2·5	3·0
20·0	0·03784	0·03789	0·03793	0·03797	0·03802	0·03807	0·03811
20·5	0·03791	0·03796	0·03800	0·03804	0·03809	0·03814	0·03818
21·0	0·03798	0·03802	0·03806	0·03810	0·03815	0·03820	0·03824
21·5	0·03805	0·03809	0·03813	0·03817	0·03822	0·03826	0·03831
22·0	0·03812	0·03815	0·03820	0·03823	0·03828	0·03832	0·03837
22·5	0·03817	0·03821	0·03826	0·03830	0·03834	0·03838	0·03843
23·0	0·03823	0·03827	0·03831	0·03835	0·03839	0·03843	0·03848
23·5	0·03829	0·03833	0·03836	0·03840	0·03844	0·03848	0·03853
24·0	0·03834	0·03838	0·03841	0·03845	0·03849	0·03853	0·03858
24·5	0·03839	0·03843	0·03846	0·03850	0·03854	0·03858	0·03863
25·0	0·03844	0·03848	0·03851	0·03855	0·03859	0·03863	0·03868
25·5	0·03849	0·03852	0·03856	0·03860	0·03864	0·03868	0·03872
26·0	0·03853	0·03857	0·03860	0·03864	0·03868	0·03873	0·03876
26·5	0·03858	0·03861	0·03865	0·03869	0·03873	0·03877	0·03880
27·0	0·03863	0·03866	0·03869	0·03873	0·03877	0·03881	0·03884
27·5	0·03867	0·03870	0·03874	0·03877	0·03881	0·03885	0·03888
28·0	0·03871	0·03875	0·03878	0·03882	0·03385	0·03889	0·03892
28·5	0·03875	0·03879	0·03882	0·03886	0·03889	0·03893	0·03896
29·0	0·03879	0·03883	0·03886	0·03890	0·03893	0·03897	0·03900
29·5	0·03883	0·03887	0·03890	0·03894	0·03897	0·03901	0·03904
30·0	0·03887	0·03891	0·03894	0·03898	0·03901	0·03905	0·03908

(4) GAS TEMPERATURE 525 DEG. F.

Per cent. standard coal.	Percentage oxygen in exit-gases.						
	0·0	0·5	1·0	1·5	2·0	2·5	3·0
20·0	0·03688	0·03693	0·03697	0·03701	0·03706	0·03710	0·03714
20·5	0·03695	0·03699	0·03703	0·03707	0·03712	0·03716	0·03720
21·0	0·03701	0·03706	0·03710	0·03713	0·03718	0·03723	0·03727
21·5	0·03708	0·03712	0·03716	0·03720	0·03724	0·03729	0·03733
22·0	0·03715	0·03718	0·03722	0·03726	0·03730	0·03735	0·03739
22·5	0·03721	0·03724	0·03728	0·03732	0·03736	0·03741	0·03745
23·0	0·03726	0·03729	0·03733	0·03737	0·03741	0·03746	0·03750
23·5	0·03731	0·03735	0·03739	0·03742	0·03746	0·03750	0·03754
24·0	0·03736	0·03740	0·03744	0·03747	0·03751	0·03755	0·03759
24·5	0·03741	0·03745	0·03749	0·03752	0·03756	0·03760	0·03764
25·0	0·03746	0·03750	0·03754	0·03757	0·03761	0·03765	0·03769
25·5	0·03751	0·03754	0·03759	0·03762	0·03765	0·03769	0·03773
26·0	0·03755	0·03759	0·03763	0·03766	0·03770	0·03774	0·03778
26·5	0·03760	0·03763	0·03768	0·03771	0·03774	0·03778	0·03782
27·0	0·03764	0·03768	0·03772	0·03775	0·03779	0·03782	0·03786
27·5	0·03768	0·03772	0·03776	0·03779	0·03782	0·03786	0·03790
28·0	0·03773	0·03776	0·03780	0·03783	0·03786	0·03790	0·03794
28·5	0·03777	0·03780	0·03783	0·03787	0·03790	0·03794	0·03797
29·0	0·03781	0·03784	0·03787	0·03791	0·03794	0·03798	0·03801
29·5	0·03785	0·03788	0·03791	0·03795	0·03798	0·03802	0·03805
30·0	0·03789	0·03792	0·03795	0·03799	0·03802	0·03806	0·03809

(5) GAS TEMPERATURE 550 DEG. F.

Per cent. standard coal.	Percentage oxygen in exit-gases.						
	0·0	0·5	1·0	1·5	2·0	2·5	3·0
20·0	0·03597	0·03601	0·03605	0·03609	0·03614	0·03618	0·03622
20·5	0·03603	0·03607	0·03611	0·03616	0·03620	0·03624	0·03628
21·0	0·03610	0·03614	0·03618	0·03622	0·03626	0·03630	0·03634
21·5	0·03616	0·03620	0·03624	0·03628	0·03632	0·03636	0·03641
22·0	0·03622	0·03626	0·03630	0·03634	0·03638	0·03642	0·03647
22·5	0·03628	0·03632	0·03636	0·03640	0·03644	0·03648	0·03653
23·0	0·03633	0·03637	0·03641	0·03645	0·03649	0·03653	0·03658
23·5	0·03638	0·03642	0·03646	0·03649	0·03653	0·03657	0·03662
24·0	0·03643	0·03647	0·03651	0·03654	0·03658	0·03662	0·03667
24·5	0·03648	0·03652	0·03656	0·03659	0·03663	0·03667	0·03672
25·0	0·03653	0·03657	0·03661	0·03664	0·03668	0·03672	0·03676
25·5	0·03657	0·03661	0·03665	0·03669	0·03672	0·03676	0·03680
26·0	0·03662	0·03666	0·03670	0·03673	0·03677	0·03681	0·03684
26·5	0·03666	0·03670	0·03674	0·03677	0·03681	0·03685	0·03688
27·0	0·03671	0·03675	0·03678	0·03681	0·03685	0·03689	0·03692
27·5	0·03675	0·03679	0·03682	0·03685	0·03689	0·03693	0·03696
28·0	0·03679	0·03683	0·03686	0·03689	0·03693	0·03697	0·03700
28·5	0·03683	0·03687	0·03690	0·03693	0·03697	0·03701	0·03703
29·0	0·03687	0·03690	0·03693	0·03697	0·03700	0·03704	0·03707
29·5	0·03691	0·03694	0·03697	0·03701	0·03704	0·03708	0·03711
30·0	0·03695	0·03698	0·03701	0·03705	0·03708	0·03712	0·03715

(6) GAS TEMPERATURE 575 DEG. F.

Per cent. standard coal.	Percentage oxygen in exit-gases.						
	0·0	0·5	1·0	1·5	2·0	2·5	3·0
20·0	0·03510	0·03514	0·03518	0·03522	0·03526	0·03530	0·03534
20·5	0·03517	0·03520	0·03524	0·03528	0·03532	0·03536	0·03540
21·0	0·03523	0·03526	0·03530	0·03534	0·03538	0·03542	0·03546
21·5	0·03529	0·03532	0·03536	0·03540	0·03544	0·03548	0·03552
22·0	0·03535	0·03538	0·03542	0·03546	0·03550	0·03554	0·03558
22·5	0·03541	0·03544	0·03548	0·03552	0·03556	0·03560	0·03564
23·0	0·03546	0·03549	0·03553	0·03557	0·03561	0·03565	0·03569
23·5	0·03551	0·03554	0·03558	0·03562	0·03565	0·03570	0·03574
24·0	0·03556	0·03559	0·03563	0·03566	0·03570	0·03574	0·03578
24·5	0·03561	0·03564	0·03568	0·03571	0·03575	0·03579	0·03583
25·0	0·03566	0·03569	0·03573	0·03576	0·03580	0·03584	0·03588
25·5	0·03570	0·03573	0·03577	0·03580	0·03584	0·03588	0·03592
26·0	0·03575	0·03578	0·03581	0·03584	0·03588	0·03592	0·03596
26·5	0·03579	0·03582	0·03586	0·03589	0·03592	0·03596	0·03599
27·0	0·03583	0·03586	0·03590	0·03593	0·03596	0·03600	0·03603
27·5	0·03587	0·03590	0·03594	0·03597	0·03600	0·03604	0·03607
28·0	0·03591	0·03594	0·03598	0·03601	0·03604	0·03608	0·03611
28·5	0·03594	0·03598	0·03602	0·03605	0·03608	0·03611	0·03614
29·0	0·03598	0·03602	0·03606	0·03608	0·03611	0·03615	0·03618
29·5	0·03602	0·03606	0·03610	0·03612	0·03615	0·03618	0·03621
30·0	0·03606	0·03610	0·03613	0·03616	0·03619	0·03622	0·03625

(7) GAS TEMPERATURE 600 DEG. F.

Per cent. standard coal.	Percentage oxygen in exit-gases.						
	0·0	0·5	1·0	1·5	2·0	2·5	3·0
20·0	0·03427	0·03431	0·03435	0·03439	0·03444	0·03448	0·03451
20·5	0·03434	0·03437	0·03441	0·03445	0·03450	0·03454	0·03457
21·0	0·03440	0·03443	0·03447	0·03451	0·03455	0·03459	0·03463
21·5	0·03446	0·03449	0·03453	0·03457	0·03461	0·03465	0·03469
22·0	0·03452	0·03455	0·03459	0·03463	0·03467	0·03470	0·03475
22·5	0·03458	0·03461	0·03465	0·03469	0·03472	0·03476	0·03481
23·0	0·03463	0·03466	0·03470	0·03474	0·03477	0·03481	0·03485
23·5	0·03468	0·03470	0·03474	0·03478	0·03481	0·03485	0·03490
24·0	0·03472	0·03475	0·03479	0·03483	0·03486	0·03490	0·03494
24·5	0·03477	0·03480	0·03483	0·03487	0·03490	0·03494	0·03499
25·0	0·03482	0·03485	0·03488	0·03492	0·03495	0·03499	0·03503
25·5	0·03486	0·03489	0·03492	0·03496	0·03499	0·03503	0·03507
26·0	0·03490	0·03493	0·03497	0·03500	0·03503	0·03507	0·03510
26·5	0·03494	0·03497	0·03501	0·03504	0·03507	0·03511	0·03514
27·0	0·03498	0·03501	0·03505	0·03508	0·03511	0·03515	0·03518
27·5	0·03502	0·03505	0·03509	0·03512	0·03515	0·03519	0·03522
28·0	0·03506	0·03509	0·03513	0·03516	0·03519	0·03522	0·03526
28·5	0·03510	0·03513	0·03516	0·03519	0·03522	0·03526	0·03529
29·0	0·03513	0·03516	0·03520	0·03523	0·03526	0·03529	0·03533
29·5	0·03517	0·03520	0·03523	0·03526	0·03530	0·03533	0·03536
30·0	0·03521	0·03524	0·03527	0·03530	0·03534	0·03537	0·03540

(8) GAS TEMPERATURE 625 DEG. F.

Per cent. standard coal.	Percentage oxygen in exit-gases.						
	0·0	0·5	1·0	1·5	2·0	2·5	3·0
20·0	0·03348	0·03352	0·03356	0·03360	0·03364	0·03369	0·03372
20·5	0·03354	0·03358	0·03362	0·03366	0·03370	0·03374	0·03378
21·0	0·03360	0·03364	0·03368	0·03371	0·03375	0·03379	0·03383
21·5	0·03366	0·03370	0·03374	0·03377	0·03381	0·03385	0·03389
22·0	0·03372	0·03376	0·03380	0·03384	0·03387	0·03391	0·03394
22·5	0·03378	0·03381	0·03385	0·03389	0·03392	0·03396	0·03400
23·0	0·03383	0·03386	0·03390	0·03393	0·03397	0·03401	0·03404
23·5	0·03387	0·03390	0·03394	0·03398	0·03401	0·03405	0·03409
24·0	0·03392	0·03395	0·03399	0·03403	0·03406	0·03410	0·03413
24·5	0·03396	0·03400	0·03407	0·03407	0·03410	0·03414	0·03418
25·0	0·03401	0·03405	0·03408	0·03411	0·03415	0·03418	0·03422
25·5	0·03405	0·03409	0·03412	0·03415	0·03419	0·03422	0·03426
26·0	0·03409	0·03413	0·03416	0·03419	0·03423	0·03426	0·03429
26·5	0·03413	0·03417	0·03420	0·03423	0·03427	0·03430	0·03433
27·0	0·03417	0·03421	0·03424	0·03427	0·03430	0·03434	0·03437
27·5	0·03421	0·03425	0·03428	0·03431	0·03434	0·03438	0·03441
28·0	0·03425	0·03429	0·03432	0·03435	0·03438	0·03441	0·03444
28·5	0·03429	0·03433	0·03435	0·03438	0·03441	0·03445	0·03448
29·0	0·03432	0·03436	0·03439	0·03442	0·03445	0·03448	0·03451
29·5	0·03436	0·03440	0·03443	0·03446	0·03449	0·03452	0·03455
30·0	0·03440	0·03443	0·03446	0·03449	0·03452	0·03455	0·03458

(9) GAS TEMPERATURE 650 DEG. F.

Per cent. standard coal.	Percentage oxygen in exit-gases.						
	0·0	0·5	1·0	1·5	2·0	2·5	3·0
20·0	0·03273	0·03277	0·03280	0·03284	0·03289	0·03293	0·03296
20·5	0·03279	0·03282	0·03286	0·03290	0·03295	0·03299	0·03302
21·0	0·03285	0·03288	0·03291	0·03295	0·03300	0·03304	0·03307
21·5	0·03290	0·03294	0·03297	0·03301	0·03306	0·03309	0·03313
22·0	0·03296	0·03300	0·03303	0·03307	0·03311	0·03315	0·03319
22·5	0·03302	0·03305	0·03309	0·03312	0·03316	0·03320	0·03324
23·0	0·03307	0·03310	0·03313	0·03316	0·03320	0·03324	0·03328
23·5	0·03311	0·03314	0·03318	0·03321	0·03325	0·03329	0·03333
24·0	0·03316	0·03319	0·03322	0·03325	0·03329	0·03333	0·03337
24·5	0·03320	0·03324	0·03326	0·03329	0·03334	0·03337	0·03341
25·0	0·03325	0·03328	0·03331	0·03334	0.03338	0·03341	0·03345
25·5	0·03329	0·03332	0·03335	0·03338	0·03342	0·03345	0·03349
26·0	0·03333	0·03336	0·03339	0·03341	0·03345	0·03349	0·03352
26·5	0·03336	0·03340	0·03343	0·03346	0·03349	0·03352	0·03356
27·0	0·03340	0·03344	0·03347	0·03349	0·03352	0·03356	0·03360
27·5	0·03344	0·03348	0·03351	0·03353	0·03356	0·03360	0·03363
28·0	0·03348	0·03352	0·03354	0·03357	0·03360	0·03364	0·03367
28·5	0·03351	0·03355	0·03358	0·03360	0·03363	0·03367	0·03370
29·0	0·03355	0·03358	0·03361	0·03364	0·03367	0·03371	0·03373
29·5	0·03359	0·03362	0·03365	0·03367	0·03371	0·03374	0·03377
30·0	0·03362	0·03365	0·03368	0·03371	0·03375	0·03378	0·03380

(10) GAS TEMPERATURE 675 DEG. F.

Per cent. standard coal.	Percentage oxygen in exit-gases.						
	0·0	0·5	1·0	1·5	2·0	2·5	3·0
20·0	0·03201	0·03205	0·03208	0·03212	0·03216	0·03220	0·03223
20·5	0·03207	0·03211	0·03214	0·03218	0·03222	0·03226	0·03229
21·0	0·03213	0·03216	0·03219	0·03223	0·03227	0·03231	0·03234
21·5	0·03219	0·03222	0·03225	0·03229	0·03232	0·03236	0·03240
22·0	0·03224	0·03227	0·03231	0·03234	0·03237	0·03241	0·03245
22·5	0·03229	0·03232	0·03236	0·03239	0·03242	0·03246	0·03250
23·0	0·03234	0·03236	0·03241	0·03243	0·03246	0·03250	0·03254
23·5	0·03239	0·03241	0·03245	0·03248	0·03251	0·03255	0·03259
24·0	0·03243	0·03246	0·03250	0·03252	0·03255	0·03259	0·03263
24·5	0·03247	0·03250	0·03254	0·03257	0·03260	0·03263	0·03267
25·0	0·03251	0·03255	0·03258	0·03261	0·03264	0·03267	0·03271
25·5	0·03255	0·03259	0·03262	0·03265	0·03268	0·03271	0·03274
26·0	0·03259	0·03263	0·03266	0·03269	0·03272	0·03275	0·03278
26·5	0·03263	0·03267	0·03269	0·03273	0·03276	0·03279	0·03281
27·0	0·03267	0·03271	0·03274	0·03277	0·03280	0·03283	0·03285
27·5	0·03270	0·03274	0·03277	0·03280	0·03283	0·03286	0·03289
28·0	0·03274	0·03277	0·03281	0·03284	0·03287	0·03290	0·03292
28·5	0·03277	0·03281	0·03284	0·03287	0·03290	0·03293	0·03296
29·0	0·03281	0·03284	0·03288	0·03291	0·03294	0·03296	0·03299
29·5	0·03284	0·03287	0·03291	0·03294	0·03297	0·03300	0·03303
30·0	0·03288	0·03291	0·03294	0·03297	0·03300	0·03303	0·03306

(11) GAS TEMPERATURE 700 DEG. F.

Per cent. standard coal.	Percentage oxygen in exit-gases.						
	0·0	0·5	1·0	1·5	2·0	2·5	3·0
20·0	0·03132	0·03136	0·03139	0·03143	0·03147	0·03151	0·03154
20·5	0·03138	0·03142	0·03145	0·03149	0·03153	0·03157	0·03160
21·0	0·03143	0·03147	0·03150	0·03154	0·03158	0·03162	0·03165
21·5	0·03149	0·03152	0·03156	0·03159	0·03163	0·03167	0·03170
22·0	0·03154	0·03157	0·03161	0·03164	0·03168	0·03172	0·03175
22·5	0·03159	0·03162	0·03166	0·03169	0·03173	0·03177	0·03180
23·0	0·03164	0·03166	0·03170	0·03173	0·03177	0·03181	0·03184
23·5	0·03168	0·03171	0·03175	0·03178	0·03182	0·03185	0·03189
24·0	0·03173	0·03175	0·03179	0·03182	0·03186	0·03189	0·03193
24·5	0·03177	0·03180	0·03183	0·03187	0·03190	0·03193	0·03197
25·0	0·03181	0·03184	0·03187	0·03191	0·03194	0·03197	0·03201
25·5	0·03185	0·03188	0·03191	0·03195	0·03198	0·03200	0·03204
26·0	0·03188	0·03191	0·03194	0·03198	0·03201	0·03204	0·03208
26·5	0·03192	0·03195	0·03198	0·03202	0·03205	0·03208	0·03211
27·0	0·03196	0·03199	0·03202	0·03205	0·03208	0·03211	0·03214
27·5	0·03200	0·03203	0·03206	0·03209	0·03212	0·03215	0·03218
28·0	0·03203	0·03206	0·03209	0·03212	0·03215	0·03218	0·03221
28·5	0·03207	0·03210	0·03213	0·03216	0·03219	0·03222	0·03225
29·0	0·03210	0·03213	0·03216	0·03219	0·03222	0·03225	0·03228
29·5	0·03214	0·03217	0·03220	0·03223	0·03226	0·03229	0·03232
30·0	0·03217	0·03220	0·03223	0·03226	0·03229	0·03232	0·03235

(12) GAS TEMPERATURE 725 DEG. F.

Per cent. standard coal.	Percentage Oxygen in exit-gases.						
	0·0	0·5	1·0	1·5	2·0	2·5	3·0
20·0	0·03066	0·03070	0·03073	0·03077	0·03081	0·03084	0·03087
20·5	0·03072	0·03076	0·03079	0·03082	0·03086	0·03089	0·03092
21·0	0·03077	0·03081	0·03084	0·03088	0·03091	0·03095	0·03098
21·5	0·03083	0·03086	0·03089	0·03093	0·03096	0·03100	0·03103
22·0	0·03088	0·03091	0·03095	0·03098	0·03101	0·03105	0·03108
22·5	0·03093	0·03096	0·03100	0·03103	0·03106	0·03110	0·03113
23·0	0·03097	0·03100	0·03104	0·03107	0·03110	0·03114	0·03117
23·5	0·03102	0·03105	0·03109	0·03111	0·03114	0·03118	0·03122
24·0	0·03106	0·03109	0·03113	0·03116	0·03119	0·03122	0·03126
24·5	0·03110	0·03113	0·03117	0·03120	0·03123	0·03126	0·03130
25·0	0·03114	0·03117	0·03121	0·03124	0·03127	0·03130	0·03134
25·5	0·03118	0·03121	0·03125	0·03127	0·03130	0·03133	0·03137
26·0	0·03121	0·03125	0·03128	0·03131	0·03134	0·03137	0·03141
26·5	0·03125	0·03128	0·03131	0·03134	0·03137	0·03140	0·03144
27·0	0·03129	0·03132	0·03136	0·03138	0·03141	0·03144	0·03147
27·5	0·03133	0·03136	0·03139	0·03141	0·03144	0·03147	0·03150
28·0	0·03136	0·03139	0·03142	0·03144	0·03147	0·03150	0·03153
28·5	0·03140	0·03143	0·03145	0·03148	0·03151	0·03153	0·03157
29·0	0·03143	0·03146	0·03149	0·03151	0·03154	0·03157	0·03160
29·5	0·03146	0·03150	0·03152	0·03155	0·03158	0·03160	0·03163
30·0	0·03149	0·03152	0·03155	0·03158	0·03161	0·03164	0·03166

(13) GAS TEMPERATURE 750 DEG. F.

Per cent. standard coal.	Percentage oxygen in exit-gases.						
	0·0	0·5	1·0	1·5	2·0	2·5	3·0
20·0	0·03002	0·03006	0·03009	0·03013	0·03017	0·03020	0·03023
20·5	0·03007	0·03012	0·03015	0·03018	0·03022	0·03025	0·03028
21·0	0·03013	0·03017	0·03020	0·03024	0·03027	0·03030	0·03034
21·5	0·03018	0·03022	0·03025	0·03029	0·03032	0·03035	0·03039
22·0	0·03024	0·03027	0·03031	0·03034	0·03037	0·03040	0·03044
22·5	0·03029	0·03032	0·03036	0·03039	0·03042	0·03045	0·03049
23·0	0·03033	0·03036	0·03040	0·03043	0·03046	0·03049	0·03053
23·5	0·03037	0·03041	0·03044	0·03047	0·03050	0·03053	0·03057
24·0	0·03042	0·03045	0·03048	0·03051	0·03054	0·03057	0·03061
24·5	0·03046	0·03049	0·03052	0·03055	0·03058	0·03061	0·03065
25·0	0·03050	0·03053	0·03056	0·03059	0·03062	0·03065	0·03069
25·5	0·03054	0·03057	0·03060	0·03062	0·03065	0·03068	0·03072
26·0	0·03057	0·03060	0·03063	0·03066	0·03069	0·03072	0·03076
26·5	0·03061	0·03063	0·03067	0·03069	0·03072	0·03075	0·03079
27·0	0·03065	0·03068	0·03071	0·03073	0·03076	0·03079	0·03083
27·5	0·03068	0·03071	0·03074	0·03076	0·03079	0·03082	0·03085
28·0	0·03071	0·03074	0·03077	0·03080	0·03082	0·03085	0·03088
28·5	0·03075	0·03078	0·03081	0·03083	0·03086	0·03089	0·03091
29·0	0·03078	0·03081	0·03084	0·03086	0·03089	0·03092	0·03095
29·5	0·03082	0·03084	0·03087	0·03090	0·03093	0·03096	0·03098
30·0	0·03085	0·03087	0·03090	0·03093	0·03096	0·03099	0·03101

Note from the Foreign Press.

Cement Testing with Wet Mortars.—By G. Haegermann. (*Zement*, 1935, pp. 529-607.)—The present standard compression tests allow the minimum strength expected from a concrete to be calculated if the water-cement-ratio is taken into consideration. Standard methods of testing are too favourable to most of the non-standardised cements, because cements with a low weight per cubic foot fill the comparatively large spaces in the standard sand to a greater extent than a normal cement and hence extra strength is obtained from a mechanical condition which does not occur with sands used in building practice. The reduction in strength due to the use of a large amount of water cannot be determined from the standard tests, nor can differences in tensile strength be found sufficiently accurately from the standard tensile strength tests. The equation $Z = \sqrt{2.6 \times D}$ holds for the relation between the tensile strength (Z) and the compressive strength (D) for standard specimens stored under water.

It is suggested that the following alterations be made in the standard specification: (1) The amount of water in the mortar should be increased; (2) A mixed sand should be used in order to hold the extra water and to avoid as much as possible the "packing" effect of cements of low specific gravity; (3) The advantages of the tensile test on prisms over the tensile test on briquettes should be examined. The paper discusses various standard specifications in the light of these suggestions.

Calculation of the Heat in the Exothermic Reaction of Portland Cement.

The following is an abstract of a paper by Messrs. H. E. von Gronow and H. E. Schwiete which appeared in a recent number of *Zement*.

The heat liberated in the exothermic reaction during the burning of Portland cement can be calculated from the chemical composition of the clinker. For this it is necessary to know the heat of formation of the calcium silicates at 20 deg. C. and the specific heats of these silicates to 1,300 deg. C. Tables I and II may be used for the calculations.

TABLE I.

AVERAGE SPECIFIC HEATS ($\bar{c}$) OF THE CLINKER MINERALS BETWEEN 20 DEG. C. AND 1,300 DEG. C. AND THE MOLECULAR WEIGHT (M).

	$\bar{c}$	M
CaO	0.2170	56.07
SiO_2, old value	0.269	60.06
SiO_2, new value	0.263	60.06
Al_2O_3	0.2763	101.94
$CaO.Al_2O_3$ (CA)	0.2579	157.01
$3CaO.Al_2O_3$ (C_3A)	0.2348	270.15
$\beta-2CaO.SiO_2$ ($\beta-C_2S$)	0.2542	172.20
$3CaO.SiO_2$ (C_3S)	0.2439	228.27

TABLE II.

	Heats of formation at			
	1,300 deg. C.		20 deg. C.	
	Cal./mol.	cal./g.	Cal./mol.	cal./g.
$2CaO+SiO_2 \rightarrow \beta-C_2S$	25.35	147.2*	29.88	173.6
C_3S from $3CaO+SiO_2$	25.35	111	29.4	129
$3CaO+Al_2O_3 \rightarrow C_3A$	22.32	82.6	20.7	76.6

* Calculated from Table I using the new value for SiO_2. If the old value $\bar{c} = 0.269$ is used the heat of formation is 149.2 cal./g.

The calculation of the heat from Table II at 1,300 deg. C. is obtained from that at 20 deg. C. in the following four steps.

(1) The formation of one molecule of the clinker minerals at 20 deg. C. sets free a certain amount of heat, which is the difference between the heats of solution of the components (e.g. 2CaO and SiO_2) and of the clinker minerals (in this case β–2CaO.SiO_2) in any acid at 20 deg. C. **+ G_1Cal.**

(2) To heat a molecule of clinker minerals to 1,300 deg. C. a quantity of heat $(1300-20)M.\bar{c}$ is required. **— G_2Cal.**

(3) In cooling the pure components the heat set free is $(1300-20)\bar{c}_{k1} \times M_{k1} + (1300-20)\bar{c}_{k2} \times M_{k2}$ where $\bar{c}_{k1}$ and $\bar{c}_{k2}$ are the mean specific heats of the minerals (e.g. SiO_2 and 2CaO). **+ G_3Cal.**

(4) x is the heat required for decomposing the clinker minerals into their components. The decomposition temperature is taken as 1,300 deg. C., but usually it is somewhat higher. **— xCal.**

According to Hess's law the sum of the heats in any complete cycle is equal to nought.

$$+ G_1 - G_2 + G_3 - x = 0. \quad x = G_1 - G_2 + G_3$$

For β-2CaO.SiO$_2$, $G_1 = 29.88$ Cal./mol. (Table II).

$$G_2 = 1280 \times 172.2 \times 0.2542 = -56.01 \text{ Cal./mol.}$$

$$G_3 = \begin{cases} 1280 \times 60.06 \times 0.263 = 20.22 \text{ ,,} \\ 2 \times 1280 \times 56.07 \times 0.2170 = 31.16 \text{ ,,} \end{cases}$$

$$+51.38 \text{ ,,}$$

$$x = 29.88 - 56.01 + 51.38 = 25.35 \text{ Cal./mol.}$$

This is the heat of formation of 2CaO.SiO$_2$ at 1,300 deg. C. and is shown in Table II. In a similar manner the values for 3CaO.SiO$_2$ and 3CaO.Al$_2$O$_3$ are obtained.

If a frozen equilibrium is obtained due to rapid cooling less 3CaO.Al$_2$O$_3$ is formed than with complete equilibrium, and it will be shown that the exothermic effect is less in this case. The large amount of tricalcium silicate which can occur in low iron melts at equilibrium gives up CaO to 5CaO.3Al$_2$O$_3$ to form 3CaO.Al$_2$O$_3$ on slow cooling The energy with which the third molecule of CaO is combined in tricalcium silicate is low, but the combination of CaO with 5CaO.3Al$_2$O$_3$ occurs with a large evolution of heat and hence the total development of heat is exothermic in the reactions

$$4(3\text{CaO.SiO}_2) \rightarrow 4(2\text{CaO.SiO}_2) + 4\text{CaO}$$

$$5\text{CaO.3Al}_2\text{O}_3 + 4\text{CaO} \rightarrow 3(3\text{CaO.Al}_2\text{O}_3)$$

Since in quick cooling these reactions do not occur a large amount of energy is held back which must be subtracted from the exothermic effect calculated for equilibrium conditions. If this does not occur Bogue's method of calculation for the clinker components is used as a basis and the content of 5CaO.3Al$_2$O$_3$ is separately determined. But there is no simple method available for this determination.

The part which 3CaO.SiO$_2$ plays as the carrier of the excess lime for the formation of 3CaO.Al$_2$O$_3$ in the burning of Portland cement is explained by this energy balance at the high temperature. The Rankin diagram enables at the same time a statement to be made about the amounts of clinker minerals present in equilibrium and the relation between the residual melt and the temperature.

The exothermic effect has been dealt with as if the clinker components had been formed from the oxides at 1,300 deg. C. Actually the Al$_2$O$_3$ in the clinker comes from the kaolin material of the clay which, after drying (endothermic) at 450 deg. C., from 900 to 1,050 deg. C. gives up 14.5$\pm$ 1 Cal./mol. corresponding to 64.4 $\pm$ 4.4 cal./g.

The energy set free during the decomposition of metakaolin is, however, not the only figure which must be taken into account in the calculation. The

silicic acid must be taken as in the amorphous condition and adds a quantity of heat when it goes into the crystalline condition. For the silicic acid contained in one molecule of metakaolin, $Al_2O_3.2SiO_2$, the heat given up is $2 \times 3.4 = 6.8$ Cal. at 20 deg. C., and about 7.2 Cal. at 900 to 1,000 deg. C. The exothermic effect due to the decomposition of metakaolin (14.5 Cal./mol.) is therefore increased by one-half $14.5 + 7.2 = 21.7$ Cal./mol., or 97.8 cal./g.

As an example a clinker will be taken with the composition 21.4 per cent. SiO_2, 9.8 per cent. Al_2O_3, and 68.8 per cent. CaO (compare F. M. Lea, *C. & C.M.*, 8, 1935, p. 35). The mineral composition according to Bogue is 52 per cent. $3CaO.SiO_2$, 22 per cent. $2CaO.SiO_2$, and 26 per cent. $3CaO.Al_2O_3$. The 9.8 per cent. Al_2O_3 present corresponds to 213 g. of pure metakaolin ($Al_2O_3.SiO_2$) in the raw material corresponding to 1 kg. of clinker. Accordingly during the formation of 1 kg. of clinker from clay and limestone the exothermic effect is:

Metakaolin	213 × 97.8 cal. =	20.3 Cal.
Formation of 520 g. $3CaO.SiO_2$.. ..	520 × 111 cal. =	57.8 ,,
,, ,, 220 g. $2CaO.SiO_2$.. ..	220 × 148 cal. =	32.5 ,,
,, ,, 260 g. $3CaO.Al_2O_3$ ..	260 × 83 cal. =	21.6 ,,
		132.2 ,,

The heat for the reactions with the pure components (oxides) is $132.2 - 20.3 = 112$ Cal. and is nearly the same as a theoretical clinker consisting only of $3CaO.SiO_2$. This has actually an exothermic effect equal to 111 Cal.

Nacken[6] gives the value of the exothermic effect as 100 Cal., and the values obtained from heating curves vary from 100 to 142 cal./g. (*Zement*, 21, 1932, p. 497). The latest investigations of the authors[7] confirm Nacken's figure.

For practical use the following method is suitable for the calculation of the exothermic effect in the formation of clinker from clay and limestone above 900 deg. C. (1) The amounts of the clinker minerals are calculated according to Bogue. (2) The metakaolin content of the raw material is obtained by multiplying the percentage of Al_2O_3 in the clinker by 2.17. (3) The amounts of the minerals present in 1 kg. of clinker are multiplied by the heats given in Table II and the values added together as in the example given. (4) The exothermic effect due to metakaolin is taken account of by adding $\%\ Al_2O_3 \times 2.17 \times 97.8 = 208 \times \%\ Al_2O_3$ if practically all the Al_2O_3 in the clinker came originally from kaolin and not from any other compound.

The exothermic effect in the formation of clinker from blast-furnace slag and limestone was 54 cal./g. at 907 deg. C. for five similar slags, and would be about 50 cal./g. at 1,300 deg. C. In exactly the same way only a small amount of heat is brought into play by the " extra " lime combined with the aluminates and silicates whether the slag used lies in the field of β-$2CaO.SiO_2$ or $2CaO.Al_2O_3.SiO_2$ (gehlenite). The exothermic effect amounts to only 50 cal./g. The heat of formation of gehlenite is not yet known, so the calculation of the exact heat of formation of clinkers made from slags of various compositions cannot be made at present.

If the clinker considered had at equilibrium a $3CaO.SiO_2$ content of 51.3 per cent., then the same clinker would have a content of 66 per cent. $3CaO.SiO_2$ with rapid cooling. $5CaO.3Al_2O_3$ must therefore be present in the clinker and its amount is equal to $\frac{1}{4}$ mol.$5CaO.3Al_2O_3$ for every 1 mol.$3CaO.SiO_2$ in excess of the amount for equilibrium conditions (in this case 66.0 − 51.3 = 14.7 per cent. $3CaO.SiO_2$). An excess of 14.7 per cent. $3CaO.SiO_2$ corresponds to $\frac{586 \times 14.7}{4 \times 228} =$ 8.6 per cent. $5CaO.3Al_2O_3$ (molecular weight of $5CaO.3Al_2O_3$ = 586, $3CaO.SiO_2$ = 228). At the same time the amounts of $3CaO.Al_2O_3$ and $2CaO.SiO_2$ fall to about one-half the equilibrium amounts. Besides this second condition (the appearance of crystalline compounds in frozen equilibrium) a third condition can occur which also is usual in practice. The liquid present in equilibrium with 66 per cent. $3CaO.SiO_2$ can be supercooled to a glass, the amount of which according to Lea is 31 per cent.

The line of equal heat generation can be drawn for the system $3CaO.SiO_2$—$2CaO.SiO_2$—$3CaO.Al_2O_3$. Its position can be easily found from the values for the exothermic effect in Table II. Above the base C_2S—C_3S—C_3A (*Fig.* 1) lies

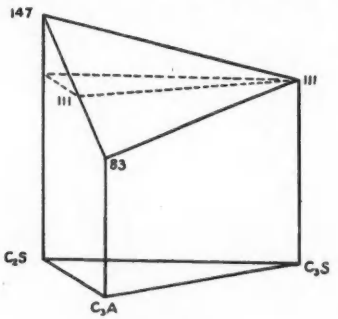

Fig. 1.

a curved 3-corner surface 83—111—147; the figures are the values of the ordinates above the base and are taken from Table II, i.e. the exothermic effect per gram of clinker mineral at 1,300 deg. C. The plane parallel to the base (dotted in *Fig.* 1) through point 111, which represents the exothermic effect of $3CaO.SiO_2$, has the straight line 111—111 in common with the plane 147—111—83. On the $2CaO.SiO_2$-side of this plane lie the cements with large exothermic effect compared with that of $3CaO.SiO_2$; on the other side lie those with small exothermic effect.

The clinker taken as an example in this paper has a heat generation of 112 cal./g. at 1,300 deg. C. and lies close to this line. If we wish to give a similar description for the second and third conditions difficulties arise in addition to that of drawing a four-component diagram. Above the base C_2S—C_3S—C_5A_3 or C_3A there is an infinite number of surfaces on which there can be points which wil give various values for the exothermic effect according to their distance from the

(*Continued on page 69.*)

(*Continued from page 68.*)

final equilibrium position of the clinker and to the amount of glass present. These surfaces are planes only in special cases. Their determination would satisfy a practical need. It is enough if the exothermic effect is calculated for slowly cooled clinker according to the method described; the amount for the non-attainment of equilibrium would be perhaps 10 to 20 per cent. higher.

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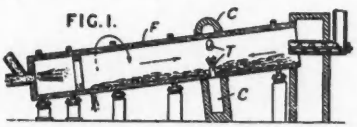
[8] H. E. Schwiete, *Zement*, 21, 1932, 362.

Recent Patents Relating to Cement.

Cements.

436,443. Basset, L. P., 7, Rue Montaigne, Paris. April 3, 1934.

FIG. 1.



In a process for the simultaneous manufacture of iron or steel and Portland cement or hydraulic lime, the charge consisting of ore, chalk for bringing the lime content of the mixture to the required value, coal for reducing the ore and the carbon dioxide of the chalk, carburizing coal and a quantity of additional coal corresponding approximately to 5 per cent. of the reducing coal for combating the oxidizing effects of the flame used, is heated in a rotary furnace by means of a flame obtained by the combustion of pulverized coal with the quantity of air to produce chiefly carbon dioxide and little or no carbon monoxide. Water vapour may be supplied to the furnace to assist in removal of sulphur from the clinker produced and air may be introduced into the furnace to burn the combustible gases therein. The process is carried out in the furnace as shown. A chamber (C) into which air is blown, the air passing into the furnace (F) through tuyères (T) to burn the combustible gases produced by the reduction of the charge. A Portland cement prepared by this process comprises 21 per cent. of silica, 6.7 per cent. of alumina 68 per cent. of lime and 5 per cent. of other ingredients.

Cements.

436,837. Triggs, W. W., 57, Lincoln's Inn Fields, London.—(Bolidens Gruvaktiebolag; 17, Västra Tradgardsgatan, Stockholm). Feb. 16, 1935.

A cement comprises calcium meta-arsenate and/or pyro-arsenate or approximately those proportions, together with lime, calcium silicate, Portland cement, aluminate cement or the like. On hydration the meta- or pyro-arsenate, which may form 20 to 80 per cent. of the mixture, combines with lime to form ortho-arsenate. Filling materials may be compounded with the cement. The calcium arsenate may be produced by allowing a solution of arsenic acid to act upon lime (quick or slaked), or limestone, the product being dehydrated at 400 to 600 deg. C. By initially proportioning the amount of arsenic acid relative to the lime, the product will be meta- or pyro-arsenate or an intermediate or neighbouring composition.

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Cements.

437,855. Soc. Anon. des Ciments de Thieu, 37, Boulevard du Régent, Brussels, and Blondiau, L., 54, Rue Mouzin, Nimy-lez-Mons, both in Belgium. Jan. 11, 1935.

In a cement composed of calcium sulphate and other ingredients, the calcium sulphate is calcined at above 850 deg. C. but below such a temperature as causes decomposition—preferably between 900 and 1,200 deg. C.—before being added to the other ingredients. The other ingredients may comprise Portland or aluminous cement, pozzolanas, limes and especially slags and slag cements. The sulphate and other ingredients may be ground together, preferably in the presence of an agent assisting grinding such as coke. The proportion of sulphate may range from 3 to 5 per cent. for Portland and slag cements to 20 per cent. or higher for "super-sulphated" slag cements.

Cements.

435,015. Bolidens Gruvaktiebolag, 17, Vastra, Trädgardsgatan, Stockholm. Feb. 16, 1935.

A cement or cement mixture contains aluminium arsenate in admixture with lime, calcium silicate, Portland cement, aluminous cement, or similar products rich in lime. The aluminium arsenate may be prepared by oxidizing arsenious oxide, As_2O_3, together with an aluminiferous material such as bauxite or clay in air, as by heating a sludge or moist mixture of the ingredients in a counter current of air in a rotating furnace, which effects oxidation and dries the mass. Catalysts for the oxidation such as iron, manganese or copper compounds, nitric acid, nitrates or nitrous fumes may be used.

Porous Concrete.

436,105. Eklund, K. I. A., 13, Regementsgaten, Malmo, Sweden. June 26, 1934.

Light concrete bodies are made of Portland slag, aluminous, or like cement, a gas-forming substance, e.g. aluminium powder, aggregate as required, and finely-divided siliceous material such as clay or silica, the mass being heated with steam to cause the silica to react with lime liberated in the setting of the cement, and also to convert di- and tri-calcium silicates into mono silicates. Suitable proportions are 20 to 60 per cent. of cement to 80 to 40 per cent. of clay. Suitable steam pressure is 12 kg. per sq. cm., to which the bodies are exposed for 8 to 16 hours. An addition of calcium chloride gives a product of increased strength: sugar enables the mass to be mixed with less water.

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